Preprint
UCRL-JC- 152955

Stability and thermal equilibrium in CICC

N. N. Martovetsky

This article was submitted to
The International Cryogenic Materials Conference (ICEC 03);
Enschede, The Netherlands; May 25-28, 2003

April 2, 2003

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

Stability and thermal equilibrium in CICC

Nicolai N. Martovetsky

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

martovetsky1@llnl.gov, FAX 925 422 7390

PACS: 74.60.Jg Critical currents

74.62.-c Transition temperature variations

Abstract

The stability of modern superconductors depends not only on the cooling and the amount of copper in the cross section of the strands but also on the smoothness of the transition from the superconducting into the normal state. Frequently the latter factor is much more important than the cooling and the copper content. Superconductors with a broad transition are more stable and easier to control than the superconductors with a sharp transition, although the price for better stability might be somewhat lower operating current.

The paper gives thermal equilibrium equations and stability criteria against small perturbations and determines the ultimate current that could be reached by a CICC depending on operating conditions. The effects of various factors (e.g., magnetic field profile, mass flow and smoothness of the transition to normal state) on the thermal equilibrium and ultimate current: are studied and discussed.

Key words: Niobium-tin, Cable-in Conduit, Critical current, N-value

Introduction

Stability in CICC (cable-in-conduit conductors) against perturbations is often associated with the transient heat removal. However, in many practical situations, the perturbations do not have a transient nature; in those cases the transient stability is not the mechanism that governs stability and serviceability of the CICC. Two typical examples of non-transient perturbations are 1) charging the magnet with current, and 2) exposing the conductor to varying fields with characteristic times longer than coupling time in CICC (typically several ms to several hundred ms). In both cases, the danger comes not from abrupt motion of the strands in the cable, but from nonuniform currents in the cable induced by varying magnetic field.

In those cases, the stability of the superconductor is determined by the quasi steady state equilibrium between the heat generation and heat transfer, and the system is stable if the following condition is met:

$$\frac{dG}{dT} < \frac{dQ}{dT} \tag{1}$$

This equation along with the steady state thermal equilibrium equation:

$$G = Q \tag{2}$$

determines the stability criterion. Here G=EI is the heat generation function, Q=hP(T-Tb) is the heat removal function, E is the electrical field, I is the transport current, h is the heat transfer coefficient and P is the cooled perimeter. For the sake of simplicity, we assume a constant heat transfer coefficient in this paper.

The material equation for the superconductor we will use in the form [1]:

$$E = E_c \exp\left(\frac{I - Ic(T_b, B_b)}{I_o} + \frac{T - T_b}{T_o} + \frac{B - B_b}{B_o} \right) \qquad (3)$$

which within 2-3 orders of magnitude is practically indistinguishable from another approximation $E=Ec(I/Ic)^N$, where the N-value defines the smoothness of the transition. Here To, Io, Bo are growth parameters by temperature, current and magnetic field, respectively, and the subscript “b” indicates background parameters at which E=Ec (I=Ic). It is easy to see that the “background parameters” and “current sharing” parameters are the same in this definition; they cause electrical field to be E=Ec.

At constant transport current and magnetic field, the solution of (1)-(3) gives the stability criterion:

$$E < E_q = \frac{hPT_o}{I_q} \qquad (4)$$

where Eq is the takeoff electrical field, or the quench electrical field, and Iq is the quench current or takeoff current. This solution is valid when differential resistance of the composite superconductor (dE/dI) is much less than the resistance of the copper stabilizer Rcu. In many practical cases of CICC this is true, so in this paper we assume it is valid. This stability criteria explains why superconductors maintain their stability at very high current densities and poor cooling, and predicts critical rates of current charge and varying fields below which superconductors remain stable [2]. The meaning of the criterion (4) is that until the electrical field in the superconductor reaches the quench field, Eq, the superconductor is stable, no matter what caused the elevated electrical field in the first place (e.g., high current density, temperature rise, varying magnetic field or high rate of current charge). At a constant heat transfer coefficient, the takeoff will take place at overheating the wire over the helium by To (typically 20-30 mK for NbTi and 0.1-0.4 K for Nb3Sn) regardless of the value of the coefficient. For more complicated heat transfer functions, it may change somewhat, but the takeoff still happens at small overheating, which has nothing to do with reaching the current sharing temperature. Since during charge or relatively slow varying field the disturbance does not represent a fast transient event that would trigger thermal conduction into helium (so called transient heat transfer, typically much higher than the steady state heat transfer to helium), formulae (4) uses the steady state heat transfer coefficient, not the transient one. This criterion can be called a stability criterion against small perturbations. The meaning of small perturbations is that they never exceed the threshold of the stable electrical field (the takeoff field). In contrast, strong disturbances bring the conductor well above stable electrical field (by an inductive heater or sudden release of significant mechanical energy) and result in recovery or normal zone propagation depending on the transient heat removal. Strong perturbations must be short in time to have a chance of recovering; small perturbations could be long or continuous.

The electrical field at takeoff can be measured directly and used as stability criteria for the estimates of serviceability if the maximum electrical fields caused by perturbations are somehow known.

Thermal equilibrium for the CICC

Figure 1 shows the schematic of the conduit, which has a length L exposed to the magnetic field and outside L the electrical field is negligible. The inlet and outlet parameters have the index “i” and “out” respectively. The thermal equilibrium equations are:

$$mCp\frac{d\vartheta}{dx} = IE \qquad (5)$$

where m is the mass flow, Cp is the helium heat capacity, ϑ is the helium temperature, which is a function of distance from the inlet. The relationship between the helium temperature and the conductor temperature is

$$EI = hP(T - \vartheta) \qquad (6)$$

The electric field could be expressed versus yet unknown temperature *T* along the length as follows:

$$E = E_i \exp\left(\frac{T - T_i}{T_o}\right) \qquad (7)$$

We can modify (6) to eliminate ϑ

$$\vartheta = T - \frac{EI}{hP} = T - \frac{IE_i}{hP}\exp\left(\frac{T - T_i}{T_o}\right) \qquad (8)$$

and substitute it into the equation (5) to obtain an equation for the temperature profile along the conductor in the uniform magnetic field:

$$mCp\frac{dT}{dx}\left(1-\frac{IE_i}{hPT_o}\exp(\frac{T-T_i}{T_o})\right)=IE_i\exp(\frac{T-T_i}{T_o}) \quad (9)$$

Introducing the following dimensionless parameters:

$$a=\frac{E_iI}{hPT_o}; \quad b=\frac{E_iIL}{mCpT_o}; \quad \theta=\frac{T-T_i}{T_o}; \quad x=\frac{x}{L} \quad (10)$$

gives the following equation:

$$\frac{d\theta}{dx}=b\frac{\exp(\theta)}{1-a\exp(\theta)} \quad (11)$$

Separating variables and integrating from x=0 to a current coordinate x using the boundary condition (at x=0, θ=0) we obtain:

$$x=\frac{1}{b}\left[1-\exp(-\theta)-a\theta\right] \quad (12)$$

where θ is the dimensionless temperature at the coordinate x, which determines the temperature and the electrical field profile.

At the outlet of the high field length *x*=*L* (highest temperature and electrical field point) we obtain an equation for the temperature θ_{out}:

$$1=\frac{1}{b}\left[1-\exp(-\theta_{out})-a\theta_{out}\right] \quad (13)$$

The condition for the takeoff is:

$$\frac{da}{d\theta_{out}} = 0 \tag{14}$$

The solution in the physical units is:

$$E_{takeoff} = \frac{hPT_o}{I_q} \tag{15}$$

Electrical field of takeoff (15) and (4) look identical, which means that the reason for the takeoff of the CICC is exactly the same as for a conductor in the helium bath – the local loss of stability. The difference is that the background temperature in the CICC depends on the accumulated heat generated by the CICC. Therefore the takeoff current will be always lower in the CICC than in the bath-cooled conductor with unlimited coolant. As in a bath-cooled superconductor, the temperature difference between the conductor and adjacent helium is To, which is 0.1-0.4 K for Nb3Sn and 0.02-0.05 for NbTi. The average electrical field integrated on the length L is:

$$E_{average} = \frac{mCp}{IL}\left(T_{out} - T_i - \frac{(E_{out} - E_i)I}{hP}\right) \tag{16}$$

Of course, the average electrical field obtainable in the CICC will be significantly less than in the equivalent bath cooled cable, providing the same heat transfer coefficient due to limited amount of helium available for cooling in the CICC. That is why the takeoff electrical fields and currents in the CICC are always lower than in the strands measured in the helium bath.

Figure 2 compares the VTC (Voltage-temperature characteristic) calculated from (12) with the measurements taken by CRPP [3]. The average electrical field is recorded versus inlet (T2) and outlet (T4) helium temperatures. The agreement is quite good considering the approximation of the heat transfer with a constant coefficient (at 400 W/m^2K) is an oversimplification.

Parameters affecting the takeoff current and electrical field

The effects of cooling, transport current, mass flow and broadness of the transition could be easily analyzed using expressions above. These parameters affect takeoff electrical field directly. Since takeoff current is a weak function of the electrical field, the takeoff current is affected less strongly, although at broad transitions the influence of these parameters becomes noticeable for the takeoff current as well. Similar findings were reported in details in [4].

Now we explore effect of the CICC length in field on the takeoff parameters. That allows predicting behavior of the magnet from short samples tests to large magnets with significantly longer voltage generating lengths.

Figure 3 shows the VTC calculated using equation (12) for the CICC tested in SULTAN [3,5] at the following parameters: I=18 kA, m=2.5 g/s at 5 bar, To=0.3K, 144 strands, wire diameter 0.81 mm. Results are shown for three different lengths of the magnetic field. At the fixed current and identical cooling conditions, the take-off peak electrical field is the same for all lengths, and the outlet temperature at the moment of takeoff is the same. Due to the accumulated heat, however, the inlet temperature of the takeoff is significantly lower for the longer lengths of the voltage generating area. The total integrated voltage is higher for the longer lengths. This coincides with the experimental observation that the long coils, like the CSMC and Inserts [6] develop much higher voltages (up to 1000-1500 μV) than the short samples of the same conductor (50-200 μV) [7] before quench. However, the average electrical field is much lower in the conductors with a long length in the field. At the same inlet temperature, the obtainable current in the short sample will be higher than in the magnet with the longer length in the field. The profile of the conductor temperature, helium temperature and the electrical field are shown in Fig. 4 for the CRPP conductor [5] as an example of the CICC. Most of the contribution to the overall voltage comes from the portion adjacent to the outlet. Thus the quench current measured in the short sample tests at the same peak field and the inlet temperature does not represent the quench current in the coil. To estimate the maximum achievable current in the coil one has to deduce the cable critical parameters and smoothness of the transition and recalculate it for the actual length in the field.

In the recent experiments on the CICC [5,6], it was observed that the transition to the normal state is significantly broader than in the original strands and that the critical current is lower than the sum of critical currents of the original strands. As we can see from (15), the takeoff electrical field is proportional to the parameter To. In [6] the N-value in the CICC went down from 20 in the strand to 8 in the CICC, which corresponds to increase of To from 0.16K to 0.4 K at 40 A per strand. That increases the stability of CICC against small disturbances by a factor of 2.5 in terms of stable electrical field. When the electrical field level is high enough, there may be no need for additional copper or more wetted perimeter to provide a sufficient amount of stability. Of course, the required stability should be determined knowing spectra of expected disturbances, but in many applications, where the high current density is essential (e.g., accelerator magnets), the main stabilizing factor is already determined by criteria (4), not by amount of copper or by transient heat transfer. The takeoff electrical field is directly defined by the To parameter. In the Nb3Sn conductors, the To parameter is 0.1-0.4K; while for the NbTi it is 0.02-0.05 K [1]. So, the NbTi CICC will be much less stable and may not even develop noticeable voltage preceding the quench. Therefore, quenches may look premature in the tests [8]. It is worth noting that the parameter directly influencing the takeoff current is To, not the N-value. The Nb3Sn conductors may have close to the NbTi N-values, but due to the different derivatives $(\delta I/\delta T)_E$, the To parameter is much lower for the NbTi CICC, and therefore the stability is much lower.

So far in our analysis we ignored the effect of the self-field and the cabling. The self-field makes the magnetic and electrical field distribution in the cross section very non-uniform [9]; this is due to cabling, which causes the strands to periodically enter the high field area, where they develop higher electrical field than in the low field area. This effect is very strong when conductors carry tens of kilo Amperes, and especially when Bo parameter of the electrical field growth is small, like in NbTi. In such conditions, the CICC will lose stability according to the criteria (15), but the average electrical field (and therefore the voltage drop across the voltage-generated length) will be significantly lower than in an imaginary conductor without the self-field effect. Because of this nonuniformity and depending on how smooth is the transition (Bo and To parameters), the CICC may quench before approaching even relatively low electrical fields like 10 μV/m. For the NbTi conductors with low Bo and To parameters, there will be a very weak or no indication that the current approaches quench, as it was observed experimentally in [8].

Conclusion

Thermal equilibrium in the CICC determines the stability of the CICC against quasi-steady perturbations. It also determines the maximum obtainable currents and voltages, after which the takeoff is unavoidable. It is shown that the heat transfer and the mass flow affect the takeoff voltage significantly, but affect the takeoff current less dramatically. The CICC with longer exposure to the magnetic field will quench at lower inlet temperatures than the CICC with shorter length in the field, but the former will develop higher total voltages before quench. Broadness of the transition to the normal state is very important parameter directly affecting stability and it is the temperature parameter of the electrical field growth To, not N-value, which governs the stability of CICC against small perturbations.

Acknowledgement

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

References

[1] G.L. Dorofeev, A.B. Imenitov, E. Yu. Klimenko, “Voltage current characteristics of type III superconductors”, Cryogenics July, 1982, p. 367

[2] E. Yu. Klimenko, N.N. Martovetsky, Stability of the superconducting wires. Modern state of the theory. IEEE Trans. On Magnetics, v.28, No. 1, January 1992, p. 842

[3] P. Bruzzone, Results from cycling tests at SecA in SULTAN, CRPP memo, June 3rd 2001

[4] E.Yu. Klimenko, N.N. Martovetsky, S.I. Novikov, “Computations of voltage-current characteristics for a stabilized inhomogeneous superconductor with thermal resistance across boundary between the superconducting wire and the substrate”, Cryogenics 1982, v7, p.367.

[5] P.Bruzzone, A. Fuchs, B. Stepanov, G.Vecsey, “Performance evolution of NbSn cable-in-conduit conductors under cyclic load”, *IEEE Trans. Appl. Superconduct*. vol. 12, No.1, March 2002, p. 516-519.

[6] N.Martovetsky, M. Takayasu, J. Minervini, T. Isono et. al, “Test of the ITER TF Insert and Central Solenoid Model Coil”, presented at ASC02, will be published in *IEEE Trans. Appl. Superconduct*. In 2003

[7] P. Bruzzone, Meeting at CRPP on the ITER Joints and Conductor performance, June 1999.

[8] P. Wesche, B. Stepanov, A. Anghel, et. al, “Comparison of strand and cable DC performance”, presentation at the Gstaad meeting, January 2003.

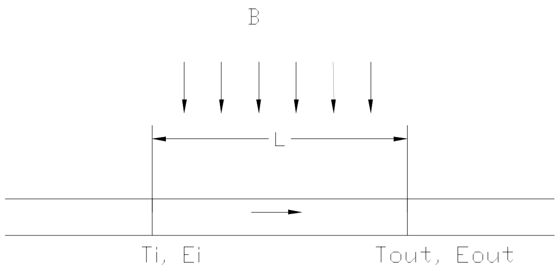
[9] N. Martovetsky,” Assessment of the CS Insert Tcs data: how do we compare conductor performance to the strand and how we make interpretations”, LLNL memo 5/18/01

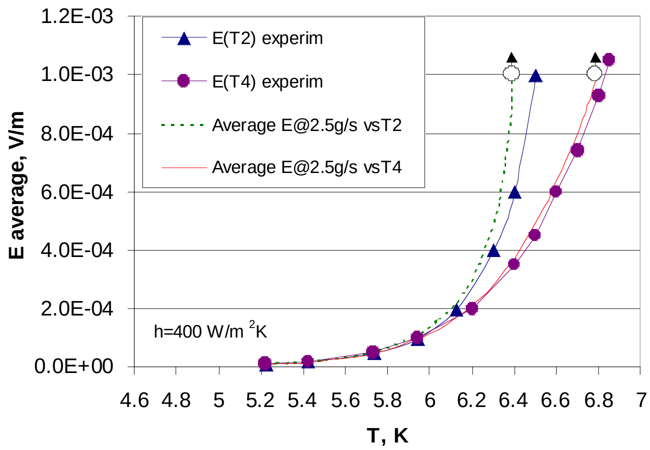
Fig. 1. CICC schematic

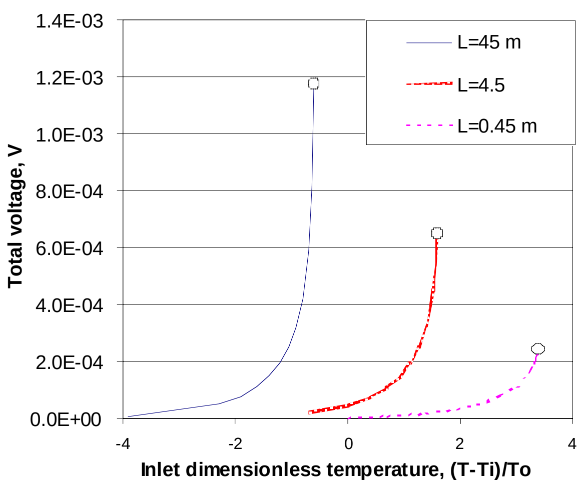
Fig.2. Comparison of calculated VTC versus test data

Fig. 3 CICC Volt-temperature characteristics for three different lengths in the field

Fig.4. Distribution of electrical field, conductor temperature and helium temperature in the CRPP conductor.


B
L
Ti, Ei
Tout, Eout


E(T2) experim
E(T4) experim
Average E@2.5g/s vsT2
Average E@2.5g/s vsT4
h=400 W/m 2K
E average, V/m
T, K


L=45 m
L=4.5
L=0.45 m
Total voltage, V
Inlet dimensionless temperature, (T-Ti)/To

E(L) distribution at m=3g/s, E2=2.8e-4V/m, I=18 kA